

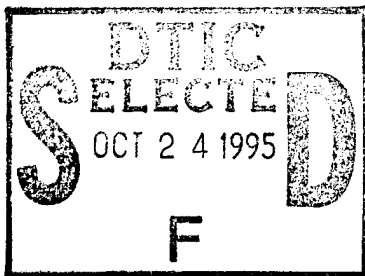
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## PRELIMINARY STUDY ON EFFECTS OF THRUST VECTORING

by

Zhao Baokai



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## PRELIMINARY STUDY ON EFFECTS OF THRUST VECTORING

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**Abstract:** With respect to the thrust vectoring technique adopted in aircraft, the paper is a preliminary study on the pneumatic properties, aircraft performance, and maneuverability after applying a two-dimensional nozzle. Some conclusions are obtained.

**Key words:** two-dimensional nozzle, thrust vectoring, hyper-torus quantity, maneuver stability, and agility.

### INTRODUCTION

In close combat of next-generation fighter aircraft, this is mainly determined by the aircraft performance and flight quality in the post-stall status. At this stage, the efficiency of the pneumatic maneuvering plane is very low, even being unable to control the aircraft; therefore, thrust vectoring control should be adopted in abnormal cases of mobility in the post-stall status.

Due to the application of thrust vectoring, the post-stall mobility becomes possible, thus further expanding the flight envelope. Thus, the flight envelope expands toward the post-stall region.

From trends in developments, the nozzle applying the thrust vectoring technique is mainly a two-dimensional nozzle. Aircraft controlled by thrust vectoring can be subdivided into aircraft completely controlled by thrust vectoring, and aircraft partially controlled by thrust vectoring. The controllability of the former is much higher than that of the latter, with more safety, convenience, simplicity, and economy, and more outstanding mobility and agility. Because of constraints at the technical level, in most cases, as presently adopted, is control of partial thrust vectoring. However, we can predict that full control of thrust vectoring should be adopted in future aircraft [1].

Thrust vectoring is realized with a two-dimensional nozzle. To deeply study thrust vectoring, we should study the effects of a two-dimensional nozzle as regards to the pneumatic properties, performance, and flight qualities of an aircraft.

## I. Variations in Lift and Drag Properties of Aircraft

The interference between the aircraft engine thrust nozzle opening and the fuselage has a considerable effect on aircraft flight performance. With different structures at the rear of the fuselage, there are differing drag percentages. In several typical dual-engine fighters, the engines typically account for

20 to 30 percent of total aircraft length; however, engine drag accounts for 38 to 50 percent of total aircraft drag. One-half of the drag due to the rear fuselage comes from disadvantageous interference and drag from different pressures in the rear fuselage range. By using a two-dimensional nozzle, interference drag and pressure difference drag can be considerably reduced during subsonic flight. Another very important aspect is that the two-dimensional nozzle itself not only contributes to the aircraft lift, but also induces the hypertorus quantity on the wings (in the trailing edge of the wings, along the rear as the nozzle ejects high-speed gas flows, thus the induced winding flow along the wing surfaces is the hypertorus quantity), thus further adding to the lift, and at the same time lowering the drag caused by lift [2]. (A two-dimensional nozzle is a rectangular shaped nozzle. It is considered that the lateral-direction flow field is homogeneous, like a two-dimensional wing; therefore, this is called a two-dimensional nozzle. Compared to the axisymmetric nozzle, structurally the two-dimensional nozzle is easily designed and the maneuver for turning the thrust direction is simple.) Therefore, in subsonic flight situations, the external drag of a two-dimensional nozzle is less than for an axisymmetric nozzle. With the same width-to-height ratio of the two kinds of nozzles, there are different resistances at the rear fuselage. When there are identical drag values for the two, the height of the rear fuselage in the case of a two-dimensional nozzle is at least twice that for an axisymmetric nozzle.

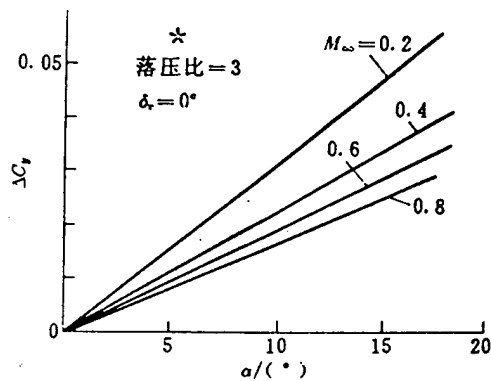


Fig. 1. Effect of angle of attack on lift due to hypertorus quantity  
KEY: \* - ratio of pressure drop

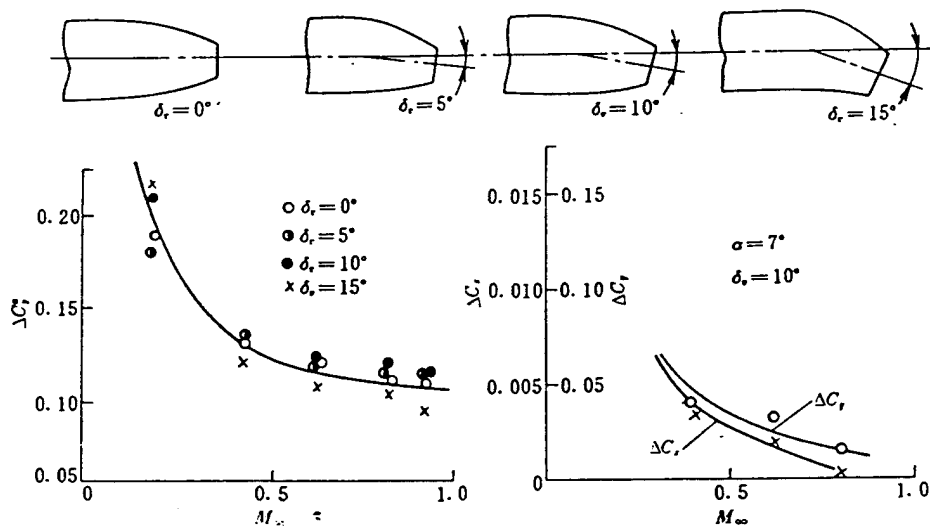


Fig. 2. Effect on M number with respect to lift due to hypertorus quantity

Figs. 1 and 2 show the effect of the hypertorus quantity on lift. From Figs. 1 and 2, during low speed the gain in lift is very large. With an increase in M number, the lift gain becomes small. When the angle of attack  $\alpha$  is between 0 and 14deg, the lift gain is a linear function of the angle of attack  $\alpha$ .

Now, we qualitatively analyze the drag variations on the

aircraft, including the effect of the hypertorus quantity. With a constant M number, it is required that aircraft always can obtain the required total lift coefficient at any thrust vector angle. Due to the existence of the hypertorus quantity, the angle of attack on the wing can be correspondingly reduced, so that the induced drag is reduced. To match the torque generated by thrust vectoring, a deviated canard wing is required, thus increasing the drag somewhat. However, by comparing the canard wing with the aircraft wing, as due to increased drag due to canard wing deflection, and the reduction in induced drag on the wing, the former is much smaller. Besides, due to the restoration of thrust, the thrust loss is reduced. The result is a reduction in total drag. From the above discussion, we know that the drag variation will be apparently different whether or not we consider the effect of the hypertorus quantity. When considering the hypertorus quantity, the maximum lift coefficient is apparently increased, however the lift-caused drag is reduced apparently.

TABLE 1. Variation of Drag on Rear Fuselage After Adopting Two-dimensional Nozzle

| 机 种 1                    | F-15 | B-1 | V/STOL | F-18 |
|--------------------------|------|-----|--------|------|
| 2 $\Delta C_{x_{尾}}$ (%) | -11  | -15 | -30    | -23  |

KEY: 1 - aircraft model    2 - [subscript] rear fuselage

TABLE 2. Variation of Cruising Range After Adopting Two-dimensional Nozzle

| 机 种 *          | F-15 | F-111 | V/STOL | YF-17 |
|----------------|------|-------|--------|-------|
| $\Delta L$ (%) | +2.0 | +6.8  | +21.0  | +7.0  |

KEY: \* - aircraft model

## II. Variation of Cruise Performance of Aircraft

Table 1 shows the drag variation at the rear fuselage by adopting a two-dimensional nozzle and by adopting the axisymmetric nozzle in the aircraft. The table lists the variation situations of several models of typical aircraft. Reduced drag will increase the flight range. Table 2 shows the variation situations of flight range for several aircraft models [3]. Due to the problem of data source, it was not possible to coordinate Tables 1 and 2 completely.

## III. Variation of Aircraft Mobility Performance

Above, the effects of the hypertorus quantity was discussed. If the span to height ratio of a thrust-vectoring nozzle (two-dimensional nozzle) becomes larger, the gas exhaust range along the trailing edge of the wing is increased, thus further increasing the effect of the hypertorus quantity.

The increased persistent speed and the instantaneous turning rate are upgrading the aircraft mobility. For example, an increase in the maximum limits shifts the left boundary in Fig. 3, thus upgrading the turning curvature of the aircraft and reducing aircraft drag, so that the persistence turning boundary curve moves upward, thus increasing the persistence turning rate

of the aircraft. As indicated by the computation in reference [4], with respect to the aircraft having control with thrust

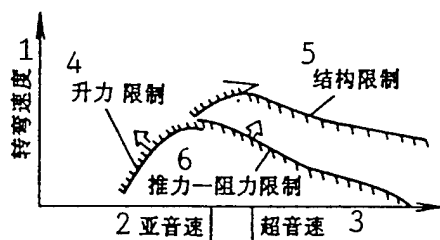


Fig. 3. Effect on turning rate due to thrust vectoring  
 KEY: 1 - turning rate 2 - subsonic speed  
 3 - supersonic speed 4 - limitation by lift  
 5 - limitation by configuration 6 - limitation by thrust/drag

vectoring, notwithstanding how fast is the initial aircraft speed, the time required to turn the aircraft 180deg is apparently smaller than for other craft; these planes include conventional aircraft, the airplanes for reduced rate of turn, and aircraft controlled by direct force. Due to the greater increase in the instantaneous turning rate, the aircraft agility is apparently upgraded; this is more advantageous to air combat.

During low speeds, the efficiency of the pneumatic maneuver plane is very low. On a number of occasions, malfunctions may occur. At this point, thrust vectoring is a very effective means of increasing stability and maneuverability of the aircraft at low speeds. Fig. 4 indicates a case when  $M$  less than or equal to 0.25 for a YF-17 aircraft; the aircraft pitch torque generated by thrust vectoring consistently maintained constant pitch acceleration of the aircraft. This capability is very important in maintaining the attitude during large angles of attack for an

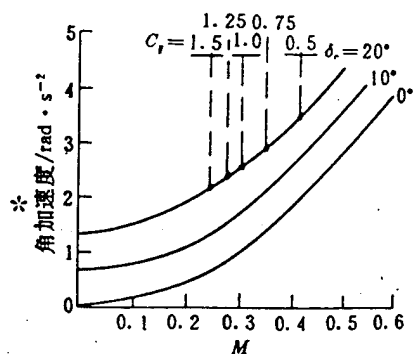


Fig. 4. Effect of thrust vectoring on pitch acceleration  
KEY: \* - angular acceleration

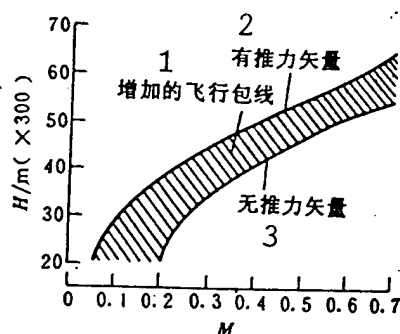


Fig. 5. Effect on flight due to thrust vectoring  
KEY: 1 - expanded flight envelope 2 - with thrust vectoring 3 - without thrust vectoring

aircraft at low speeds. This is also a necessary means of post-stall maneuvering of the aircraft.

In the case of F-15s, after  $M$  less than or equal to 0.4, since the velocity head is relatively low, the pitch maneuvering torque generated by the vertical rudder is reduced. Now by using thrust vectoring control, the pitch effectiveness can be almost doubled. Therefore, the aircraft flight envelope extends leftward, as shown in Fig. 5.

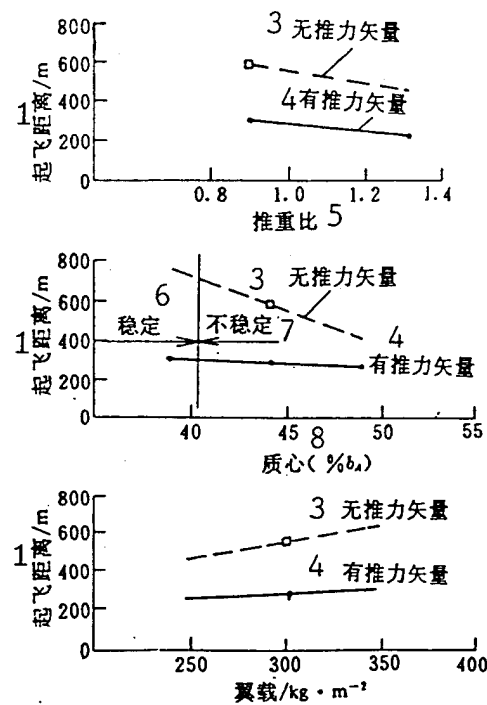


Fig. 6. Effect on takeoff roll distance of thrust vectoring

KEY: 1 - takeoff distance 2 - wing loading  
 3 - absence of thrust vectoring 4 - with thrust vectoring  
 5 - thrust to weight ratio 6 - steady  
 7 - nonsteady 8 - mass center

#### IV. Variation of Takeoff and Landing Performance

A requirement of tactical techniques of the next-generation fighter craft is to reduce the distance needed for takeoffs and landing as much as possible. In particular, this requires the capability of takeoffs and landings on runways or short decks on an aircraft carrier with damages caused by enemy bombs. The running distance of such aircraft should be less than 400m. Since the thrust to weight ratio of the aircraft is larger, the problem of short takeoff distances is not as striking as that of

short distance landings. Especially for aircraft with thrust vectoring control, the takeoff distance is shorter. By relying on thrust vectoring control, when the speed is very low, the pitch thrust vector deflects upward so that the front wheel of the aircraft is lifted. With the lowered deflection thrust vectoring, the aircraft leaves the ground very quickly. The short-distance landing requires that an aircraft should have high lift and drag, at the same time.

Fig. 6 shows the result of the aircraft model on the same principle [5]. The aircraft has a canard configuration with delta wings, but only with a pitch thrust vectoring control. The figure shows the effects on takeoff distance due to the thrust to weight ratio, position of the center of mass, and wing loading of the aircraft. The thrust to weight ratio is 0.89; the position of mass center is  $44\%b_A$ ; the wing loading is  $302 \text{ kg/m}^2$ , with dry runway, 0m sea level, and ambient temperature: 15C. From Fig. 6 we can see that with different thrust-to-weight ratios, thrust vectoring nearly halves the takeoff and landing roll distances at different thrust to weight ratios. While moving rearward the mass center, the roll distances are slightly decreased, but much smaller than the case without thrust vectoring control of aircraft. With increased wing loading, the takeoff roll distance is increased. For comparison, the increase in roll distance is relatively large in the case of the absence of thrust vectoring control of the aircraft.

Thrust reversal can considerably shorten the landing roll

distance of aircraft, and is not sensitive to the runway status. Fig. 7 shows the situations of F-15s. From Fig. 7, thrust reversal can reduce landing roll distances by approximately two-thirds without being related to total aircraft mass. Whether for dry or wet runways, the roll distance does not change, apparently.

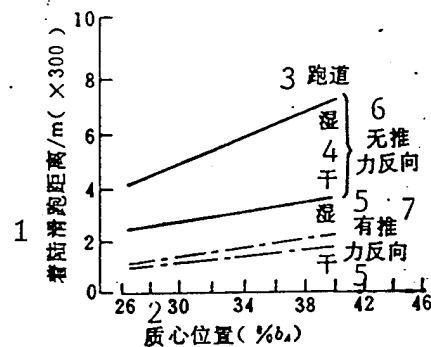


Fig. 7. Effect on landing roll distance of thrust reversal

KEY: 1 - landing roll distance 2 - position of mass center 3 - runway 4 - wet 5 - dry 6 - without thrust reversal 7 - with thrust reversal

TABLE 3. Variation of Landing Roll Distance After Adopting Thrust Vectoring

| 机 种 1     | F-111 | <del>YF-17</del> | 2 先进飞机 |
|-----------|-------|------------------|--------|
| 着陆滑跑距离 3  | 14.4  | 11.0             | 50.0   |
| 减小量 (%) 4 |       |                  |        |

KEY: 1 - aircraft model 2 - advanced aircraft 3 - landing roll distance 4 - percentage of reduction

Table 3 shows a comparison of variation of landing roll distance for several models of aircraft by using thrust vectoring [3].

From Table 3, when thrust vectoring is used for controlling an aircraft currently deployed, the decreased magnitude of the landing roll distance is approximately the same, not very significant. The reason is the following: when applying thrust vectoring control, at the same time a canard wing should be installed to coordinate the torque generated by thrust vectoring. However, the maneuverability of the canard wing is not large. In addition, the size and position of the canard wing are restricted by the original aircraft configuration.

## V. Conclusions

From the foregoing descriptions, after an aircraft is brought under thrust vectoring control, many aircraft performance indicators are upgraded, to differing extent. Since the existence of the hypertorus quantity, the drag is decreased with a gain in aircraft lift; this is especially significant at low speeds. Due to the reduced overall aircraft drag, the navigation range is increased. Thrust vectoring control increases the persistent turn rate and the instantaneous turn rate of the aircraft, thus considerably upgrading aircraft agility. Especially at low speeds, thrust vectoring control greatly upgrades the aircraft maneuverability and stability, thus considerably upgrading the close air combat performance of the plane. By using thrust vectoring control, the roll distance of the aircraft is decreased; the takeoff roll distance is much more decreased than the landing roll distance. Only by adopting the

reversing thrust vectoring control can the landing roll distance be apparently reduced. With complete thrust vectoring control, the landing roll distance of an aircraft is decreased very significantly.

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